Reponse to Reviewer 1

1 Summary

The authors provide a comprehensive assessment of the impact of void-filling routines on the calculation of glacier elevation and volume changes. This is an important work that has relevance for a wide variety of both local and regional scale glacier change studies utilising geodetic datasets. This is a timely study and a topic I've been interested in for some time. The manuscript is of high-quality, is very well written, largely free from errors, and suitable for publication in The Cryosphere. I would recommend acceptance following minor revisions, providing that the authors address the following minor comments. I'd like to congratulate the authors on an interesting study and an important addition to the growing body of knowledge on regional-scale glacier volume change estimation. This paper will be an excellent companion to the equally good Nuth & Kaab TC study of 2010.

We would like to thank the referee for their careful and constructive comments that have helped to improve both the clarity and focus of the manuscript. Our responses to the comments below are in blue, with the original comments in black.

2 Minor comments

- Title: There is an inconsistency between the use in the title of the term geodetic mass balance' and what is referred to elsewhere in the manuscript (and what is actually calculated) which is volume change. I know why you have it up front in the title, as this is motivation for the study, but as you calculate only relative estimates of volume change' (4,23-24), the title is in fact incorrect. You do not assess the sensitivity of geodetic glacier mass balance in this work. The title therefore needs to be revised to volume change'. However, keep the geodetic mass balance mentions in the abstract and elsewhere, as they're used correctly there, and provide the important context to this work.

  We agree, and have changed the title to better match the text.

- page 1, line 18: can provide

  Changed.

- 1,21: has been calculated

  Changed.

- 1,24-25: this isn't quite right, though may just be a quirk of language. The geodetic method does not have to require extrapolation of sparse measurements, but it still can if measurements are sparse. Centreline elevation changes extrapolated to full width and differenced are still the geodetic method' (see, for example, Arendt references in your list). A couple of other studies, including one of mine, have directly compared mass balances calculated from full coverage DEMs and extrapolated centreline elevations (Barrand et al., 2010, J. Glaciol., 56, 199, doi:10.3189/002214310794457362).

  Added a parenthetical statement to make clear that we aren't excluding, for example, laser altimetry/ICESat studies from the 'geodetic' label.

- 2,4: not sure glacier water resources' is quite the phrase you're looking for as that gets into ice thickness / total water equivalent volume territory. Perhaps something like the scale of glacier change'?

  Changed to 'scale of glacier change.'

- 2,35: I know you detail from where the DEMs are from later, but this sentence is fragmentary and would benefit from a very brief description of the source of the data.

  See response to next comment.

- 3,1-2: this sentence is strange. So, you're measuring volume changes but we should not interpret these as mass balance estimates? Why would we, given the additional density correction step that is necessary to calculate mass change? Why not calculate volume changes only (and present these) and avoid any mention of mass balance entirely? Then you solve the problem of seasonal timing. This looks to be what you've done (from the following sentence). If the estimates presented here . . .should not be interpreted as mass balance estimates..', then you need to change the title of the paper and the content of the abstract, to reflect this.

  We have moved this sentence to the end of the paragraph, and included information about where the DEMs come from (C-band vs. X-band). We have also made it clear that additional corrections (density, seasonal timing) must be made before these values are interpreted as mass balances. Additionally, we have made it more clear that we are looking at the effects on volume changes, which can then be used to estimate mass balances, in response to your previous comment.

- 17,1: it's not clear to me why the elevation data in this figure should be presented in a categorised colour scale. I think it would be clearer to view and interpret if the background hillshade was slightly opaque, and the DEM data were presented in a continuous colour scale. The dark grey outlines are presumably the ice-covered land, though this is not specified in the figure itself or the caption. With a more opaque hillshade, the ice cover would then be more discernable.

  The color scale is continuous, but QGIS displays the legend as a non-continuous scale. We have added a continuous color scale to the legend, specified what the dark outlines are, and increased the transparency of the background hillshade.

- 3,9-14: I don't think there is, but is there any reason to believe that findings from a single DEMs scene from this region would differ from elsewhere in the world (perhaps regional differences between SRTM tiles?). Can you justify here why this study uses just a single difference DEM from this location, rather than multiple difference DEMs from elsewhere?

  We don't believe that there would be a significant difference in the results from this region vs. another region, in part because of the diversity of glacier types, sizes, etc. that are found in this region. The reason to choose a single DEM difference is that then the results are not dependent upon variations in the changes through time. In this respect, the effects of void interpolation is most easily extracted and understood using a single DEM difference. By using a large collection of varying glaciers in one region, we also simulate something similar to multiple DEM differences over one glacier.

- 3.20: qualify here that SRTM is commonly used at regional-scales and over medium to long time periods as it is not exceptionally accurate and likely wouldn't be as much use for e.g. 2000-2001 mass balances.

  Added a clause, "though typically over longer time periods (> 10 year separation between DEMs)." to this sentence.

- 3,24-30: due to these problems, would it not have been better to select a region for which two high-quality regional-scale DEM products exist? Say, Iceland?

  Perhaps, but finding high-quality, regional scale DEM products with known dates is not an easy task. For example, the Iceland National DEM has significant errors/interpolation artefacts, as many areas are

interpolated from old topographic contours. While the glacier surfaces may be quite good, these artefacts and errors make estimating the uncertainty in the calculated volume changes much more difficult. In response to another reviewer, we have provided additional information about the size of the area impacted by these voids.

- 4,11-12: what's the justification for this omission now that we know that these very small glaciers are quite important? (Bahr & Radic, 2012, Cryosphere, doi:10.5194/tc-6-763-2012).

  We omit these smaller glaciers because errors/inaccuracies in glacier outlines are much larger for smaller glaciers. As our goal is to investigate the effects of void interpolation methods on estimated volume changes, it is best to have a larger sample of on-glacier pixels to work with; voids over small glaciers result in more limited data from which to extrapolate. Also, since our objectives are methods oriented, the question about small glaciers being important is not so relevant. For further comparison of results over small glaciers, we would suggest that higher spatial resolution DEMs are required as opposed to the medium resolution DEMs used here. We have attempted to clarify this in the manuscript. We now clarifiy this in the text.

- 5,1-2: specify most spaceborne stereo optical sensors'. Sensors onboard airborne platforms or historical aerial photographs will not have identical spectral range or resolution, and therefore may not be comparable with processing of ASTER scenes.

  Done.

- 5,13: mean and median, or the mean or median? Which? See also 6,7-8.

  Mean or median; changed to clarify.

- 5,20: if this is to be replicable then some more detail is required. Which surrounding pixels? Just those immediately proximal to the void? If so, this could be problematic as there may be inaccurate elevations just beyond the low correlation areas cutoffs. If not the very next pixel, then how many back from the void space? Provide enough detail of this method for another to reproduce your procedure exactly. See also 5,25

  The interpolation is carried out using `scipy.interpolate.griddata`, which triangulates the input data and performs linear barycentric interpolation (`https://docs.scipy.org/doc/scipy/reference/generated/scipy.interpolate.griddata.html`). We will make the scripts used to fill the voided DEMs, as well as a csv file of resulting volume changes, available through a github repository upon the acceptance of this paper.

- 6,26: why 10%? What's your justification?

  The 10% assumption is based on a conservative estimate of the error reported by the RGI (e.g., Pfeffer and others, 2014), found elsewhere in the literature (e.g., Brun and others (2017); Kääb and others (2012)). We have added these references to the text.

- 6,27: over what scales does spatial autocorrelation occur? I see this on the next page. But, why is it assumed to be 500 m (and why only 500 m given that it can occur on a range of scales simultaneously)?

  We have chosen 500 m based on the value used in other studies, including Brun and others (2017); Fischer and others (2015); Rolstad and others (2009); Magnússon and others (2016). We are aware that it could be smaller, but feel that 500 m is a good, conservative estimate based on this previous work.

- 18, Figure 2: Can you differentiate between the colour of the glacier outline and the ASTER correlation score mask? The middle panel all looks the same colour to me (except the red), even though I think its supposed to be dark grey outline and black mask.

  Done.

- 19, Figure 3: Shaded grey around elevation changes refers to uncertainties? If so, please state in the caption.

  Mean ± one standard deviation, now included in text.

- 7,9-10: why would you find the most voids occurring in the middle of the elevation range when from an optical image feature matching perspective (where the ASTER DEM gets its correlation score) you would expect fewer features and poorer correlation the higher up you go?

  For most of these glaciers, the higher elevations are on much steeper slopes with significantly higher contrast. The middle elevation ranges tend to be the flatter, more featureless parts of the accumulation area.

- 20, Figure 4: Background Landsat scene is a bit awkward to see as its so dark. Can you adjust the contrast, or similar to a previous comment, turn up the opacity to de-emphasise the background and emphasise the elevations changes? Looks like a graded colour scale, yet legend shows categories. Shouldn't the legend by a graded colour bar too? Likewise other figures.

  Regarding the color scale, see comments for Figure 1. We have changed the background to be a pan-sharpened Landsat scene with more contrast.

- 7,18: by acquisition area, do you mean accumulation area? If you're going to list individual glacier names in the main text, these need to be listed or shown in the figure somehow.

  In this case, we are referring to the 2012 and 2013 acquisition years for the IfSAR DEM, not the glacier accumulation areas. Glacier names are shown in Fig. 1, which we now refer to here.

- 7,24: I would say patterns' isn't quite the right word here. Some of the variability' perhaps?

  Changed.

- 7,25-26: is it therefore worthwhile to consider repeating this exercise at the local glacier (rather than regional) scale? And for simple vs complex perimeter glaciers?

  It could be interesting to consider the local glacier as well, but this will be heavily dependent upon each individuals glacier change with the amount and location of voids. In this study, the local scale is covered by about half of the extrapolation methods applied (See Figs. 5, 7, and 8). Furthermore, it is not necessarily the perimeter of the glaciers that's important here, it's the variability in elevation changes, where you have some surging/advancing glaciers, many heavily retreating glaciers that reach low elevations, and other glaciers that are also retreating, but don't necessarily have the same loss vs. elevation as larger glaciers due to dynamics.

- 23, Figure 7: Great figure, but for readability perhaps the RGI60.01.' part can be removed from each individual glacier on the y axis and be included in a single y axis label? Can you also indicate in the figure caption how the individual glaciers are sorted along the y axis? It doesn't appear to be by RGI ID number, or by volume change. Is it north-south, or by glacier area, or something else?

  Thank you. We have adopted your suggestions, and added "sorted by glacier area in descending order" to the figure caption.

- 24, Figure 8: It would be interesting to see this analysis extended to smaller glaciers, or the entire sample, but I understand if this is too time-consuming and therefore not possible.

  In general, the pattern is similar for the smaller glacier classes, just with more outliers.

- 9,1-20: some very small paragraphs here (comprising just one sentence sometimes). Is this necessary?

  We have combined the last two paragraphs, and added to the paragraph beginning at line 6.

- 9,18-20: can you add some value judgments between these best three, perhaps quantifying precisely how each do and therefore which performs best? Actually, nevermind that, I see it in the next paragraph.

  Never minded.

- 11,8: please quantify rather than just stating performed well'.

  Added "producing estimates within the uncertainty of the original estimates"

- 11,20-25: please replace do well', does well' etc, with perform(s) well'.

  Done.

References

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